'RESEARCH ON ENERGY ABSORPTION BY NONWOVEN FABRICS'

FINAL TECHNICAL REPORT

by

J.W.S. Hearle & A.T. Purdy

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13. ABSTRACT
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Previous work has been reviewed and its relevance to the ballistic problem analysed. An existing theoretical approach to the dynamics of impact has been extended and provided the possibility that fabric protection capability could be roughly calculated from data generated during a simple tensile test (U).

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ABSTRACT

The object of this work has been to gain a greater understanding of the means by which needled fabric absorbs energy when struck transversely by a projectile.

To this end needle punched fabric has been subjected to a slow speed penetration test using a rigid steel probe, and to impact with a free flying projectile. The first method of test helped establish the mechanism by which this material deforms during impact. During high speed tests deformation was studied using high speed ciné photography and various phenomena observed; these included the initial inward movement of fabric during impact, the presence of broken fibres on projectile emergence, and the nature of projectile emergence. Detailed observation of fabric behaviour around the impact point when multilayer samples are in use has been carried out using an embedding and sectioning technique. It seems that projectiles extend fabric until its thickness is reduced to such a level that no further resistance is offered.

Previous work on the structure and mechanical properties of needled fabric has been reviewed and its relevance to the ballistic problem analysed. An existing theoretical approach to the dynamics of impact has been extended and provided the possibility that fabric protection capability could be roughly calculated from data generated during a simple tensile test.

CONTENTS

CHAPTER I

INTRODUCTION

1. General

It has previously been shown that needle punched fabric can be utilised to good effect as a means of stopping fragment simulator projectiles. Interest has thus been created in the possible use of this material as the protective element within fragmentation vests issued to combat troops. The current protective element within vests consists of twelve layers of a basket weave 14oz/sq.yd. nylon fabric, producing a medium sized vest weighing 8½ lbs.

The advantage of needled fabric for ballistic purposes is that at low areal densities it is possible to produce felts at half the weight of this standard woven fabric while still retaining 92% of its ballistic protection. At high areal densities (18 oz/sq.ft.) the protection offered by both fabric and felt is essentially the same. Thus a recent military specification (1) demands that six layers of 12 oz/sq.yd. nylon felt shall provide protection against a fragment simulator projectile travelling at between 1050 and 1135 ft/sec; for the standard woven assembly the specified velocity (2) is 1225 ft/sec.

2. Present State of Knowledge

Previous experimental and theoretical work on the application of needled fabric for ballistic purposes has been documented by Laible and Henry (3). They have cited various fibre and fabrication parameters which may affect ballistic resistance and discussed their importance on the basis of work already done. This has made apparent the gaps in present knowledge, many being caused by the tedious and difficult experimentation required to fully understand several factors. The majority of experimental work has involved the manufacture of fabric in which fibre and fabrication parameters have been varied, with subsequent V50* ballistic testing to establish whether the particular modifications have been successful.

The notable exception to this is the work of Ipson & Wittrock (4) who devised the Spark Gap Technique as a means of studying in detail the pattern of deformation during a needled felt-projectile interaction. They were able to plot displacement-time, velocity-time and force-time graphs for the impact process. Based on their experimental findings a predictive equation was produced which is accurate when impact velocity is well below the ballistic limit. However, as impact velocity approaches ballistic limit velocity the discrepancy between theory and experiment increases sharply.

Ehlers and Angelo (5) have produced an empirical equation relating the V50 limiting velocity to felt parameters. The validity of this equation over a wide range of felt materials has not been checked.

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* The V50 ballistic limit, a statistical quantity, is interpretable as the striking velocity at which 50% of individual impacts within a velocity range of 125 ft/sec will result in complete penetration.

Apart from detailed knowledge gained concerning the effect of various parameters on ballistic resistance, some general information relating to needled felt-projectile impacts has been gathered. Circular fabric specimens deform into a conical shape on impact and a large area of fabric is affected by the collision. It is necessary that the felt be allowed to respond freely to the impact process or maximum resistance is not realised. When thick felts are tested this free response is not possible, momentum is not transferred from projectile to felt and breakdown occurs more easily. This is why at high areal densities the efficiency of felt material is reduced to that of the standard woven fabric.

3. Previous work on Needled Fabric.

Comparatively little scientific work has been published on needle punched fabric. However, it is thought relevant in this report to include brief details of these studies, so that any information which may be useful in solving the ballistic problem is made available.

Most attention has been paid to the influence of various factors on the tensile characteristics of needled fabric as measured by a uniaxial tensile test that can be performed on an Instron Tensile Tester at constant rate of elongation. Values of fabric tenacity, breaking extension, initial modulus and the general shape of the stress-strain curve have been compared for fabric made by variation of the machine and web parameters which will be discussed in Chapter II. The ultimate aim of this work has been theoretical analysis of the relationship between fabric structure, mode of deformation and ultimately fabric tensile properties, as a means of isolating the importance of various factors in producing strength within the needled structure. One such attempt has been published (6) but is in the process of being revised (7) in the light of more recent knowledge of fabric structure (7,8). A discussion of the general principles underlying the origin of strength in a needled structure has been presented by Hearle (9).

The effect of web and fabric weight on fabric properties has been shown (10), along with variations caused by change in web structure and the direction of test. Machine parameters such as needling density and depth of needle penetration interact with web weight in their influence on tensile behaviour (7,11), making their individual effects difficult to isolate and characterise. Changes induced by the stretching, shrinkage and reinforcement of needled fabric have been considered (12), and also the influence of fibre type and dimensions (13).

The incorporation of anti-slip compounds such as colloidal silica (syton) in needled fabric for ballistic purposes has been suggested (5). The effect of such treatment on fabric tensile properties has been shown by Hearle and Husain (14). Treatment of fibres with syton before processing caused a deterioration in mechanical properties of the fabrics subsequently produced. In this case high friction must cause poor behaviour in processing, which was confirmed by Baer Sorter diagrams for the fibres at

different stages of fabric production. In contrast, treatment of the needled web produced an improvement in mechanical properties, because an increase in friction within a preformed needled structure causes greater resistance to extension and a consequent increase in strength. It is not easy to relate these findings to effects on ballistic resistance without performing the necessary experimentation. Excessive resistance to extension will reduce the ability of felt to stop projectiles by causing fabric breakdown through fibre breakage.

4. The Present Approach

The object of this work is to isolate the means and mechanisms by which needled fabric absorbs energy during impact with a high speed projectile.

Our previous work on needled fabric structure and mechanical properties has been reviewed, with the aim of exposing any information which is relevant to the ballistic resistance and energy absorbing capabilities of this material.

A preliminary study of the behaviour of needled fabric subject to transverse impact was carried out using a slow speed test, which involved the penetration of a steel rod through fabric. This provided information concerning the basic deformation mechanism operative within the fabric during impact, and showed how a greater fabric area becomes involved in providing resistance as loading increased.

The impact of a free flying projectile with fabric has been studied by means of high speed cine photography in the attempt to isolate means by which energy is transferred from projectile to fabric, and to observe final breakdown on the occasions when projectile velocity was too great to be nullified by the fabric. Various occurrences during impact have been isolated, and it has been possible to study changes in deformation as additional fabric layers were added to the specimen under test.

The deformation of individual layers within multi-layer samples which stopped projectiles has been studied by means of an embedding and sectioning technique.

CHAPTER II

NEEDLE PUNCHED FABRIC

1. Introduction

As this work is primarily concerned with needle punched fabric it is considered necessary to include some discussion on the nature of this material. Such information will facilitate understanding of suggested deformation mechanisms and provide an up to date account of our knowledge on the relationship between the structure and mechanical properties of needled felt. These ideas can then be applied to the ballistic problem.

2. General Nature of the Structure

The process of needle punching employs barbed needles to reorient some fibres originally in the horizontal place of a card web into the vertical direction. It is unlikely that the whole length of a fibre will be transferred into the vertical plane (unless breakage occurs), and this contact between fibres in both fabric planes increases tensile strength above that which would be possible if two distinct levels of structure existed. It is thought that any factor which destroys or reduces this contact (such as excessive depth of needle penetration) will cause a decrease in fabric tenacity; this has been shown in the case of needle penetration at certain web weights (7).

Thus fundamentally needled fabric structure consists of a series of vertical fibre pegs joined by arcs of fibre. Between these pegs pass fibres which have not been disturbed during needling (this will depend on needling density) and around them pass fibres which have not come under the direct influence of needles but have been pushed aside to make way for the vertical structure.

The pegs or tufts are themselves formed by the release of fibres held by needle barbs during punching. Fibres loop round barbs and are often left in this configuration within the fabric (8), unless fibre breakage takes place and the loops are broken. Under these conditions the peg is left as a cylinder of fibres, although the work of Gardmark and Martensson (15) has shown that theoretically a vertical fibre tuft should take the form of an inverted cone. They showed that half the reoriented fibres are picked up from the top fifth of the web, with successive smaller amounts reoriented from succeeding layers.

A study of Fig (1) will clarify this description. This is a machine direction cross-section of needled material made from a web the top 20% of which was coloured fibre making the vertical structure more easily visible. It is not possible at this time to tell whether any one fibre exists in adjacent pegs and the arc joining them, but this must occur especially at high needling densities. As mentioned earlier this should have the considerable effect of increasing fabric strength.

The horizontal structure of needled fabric is difficult to characterise as it is based on the structure and fibre orientations in the original card web. Only generalisations such as that in parallel laid fabric fibres pass around the circular tufts in elliptical fashion, can be made. In cross-laid fabric fibres pass round the tufts in two directions giving a more regular appearance to the points of contact between the horizontal and vertical structure. This variation in the card web and subsequent needled structure has considerable influence on fabric properties as will be shown later.

3. Factors affecting structure

(a) General:

There are numerous factors which affect the structure of a fabric made by needling. Their influence on structure is reflected in fabric mechanical properties and is thus of relevance here. These variables can be divided into two categories, web and machine parameters as shown below.

WEB	MACHINE
Weight (thickness)	Web movement/loom cycle
Structure	Depth of needle penetration
Composition – fibre type – fibre dimensions	Needle Variables – blade gauge – number of barbs – barb size

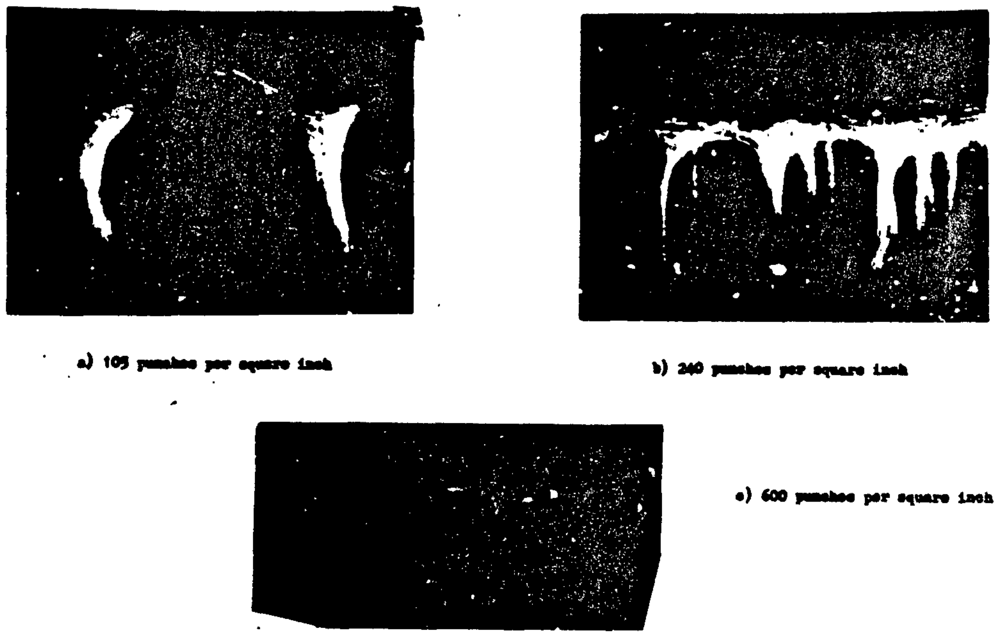
Each is worthy of a brief mention.

(b) Influence on vertical structure

When a web is made heavier by increasing the number of layers in its make-up then it becomes thicker, and for a given depth of needle penetration below the bed plate more of the needle enters the web providing an opportunity for increased fibre pickup.

If a web structure presents a range of fibre orientations to a penetrating needle, it is to be expected that more will be picked up than if all the fibres lie in one direction. Punching force measurements (16) have confirmed this; over a range of web weights (before breakage during needling interferes) higher forces were recorded when punching cross-laid material than with parallel laid fabric.

Fibre coefficient of friction and the density of the web produced govern the effect of fibre type on reorientation; more fibres will be picked up when needling a dense web or one in which high frictional forces exist between constituent fibres. An increase in fibre length within the web causes a decrease in the number of fibres reoriented, because for a given weight a web containing longer fibres will be less dense. Fibre diameter determines the number of fibres which can be held for a given barb size and shape.



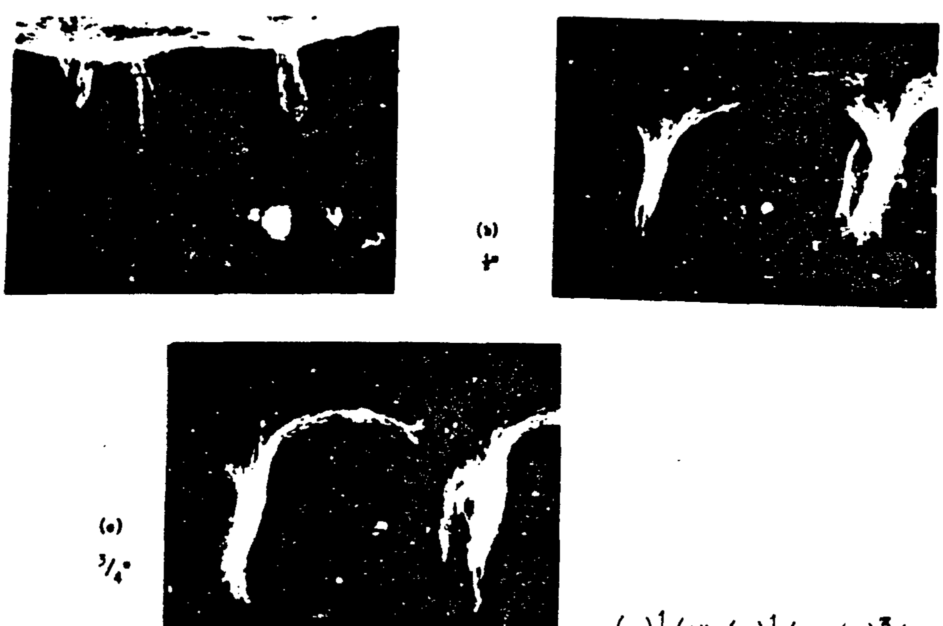
a) 105 punches per square inch

b) 240 punches per square inch

c) 600 punches per square inch

Figure 1

EFFECT OF NEEDLING DENSITY ON FABRIC VERTICAL STRUCTURE



(a) 1/4"

(b) ½"

(c) 3/4"

(a)1/4" (b)1/2" (c)3/4"

Figure 2.

EFFECT OF NEEDLE PENETRATION ON FABRIC VERTICAL STRUCTURE

The effect of web movement per loom cycle and hence needling density on fabric vertical structure is not immediately apparent. Fig.1 illustrates the effect on vertical structure of needling the same web (viscose rayon $2\frac{1}{2}$" 3 den, weight = 427 g/m^2) at $\frac{1}{2}$" penetration and the needling densities shown. A study of the photographs shows that an increase in needling density reduces fabric thickness (because of the increase in number of fibres reoriented per unit area) and also the number of fibres reoriented per needle insertion. This latter fact can be explained as follows. The closer together consecutive needle penetrations the greater the restrictions placed on fibre movement by previous insertions, and hence fewer of the fibres which come into contact with a needle are able to move sufficiently within the web to be pulled down into the structure.

Fig. 2 illustrates the effect of needling the same web (viscose rayon, $2\frac{1}{2}$" 3 den, weight = 564 g/m^2) at 105 punches per sq. inch and various penetrations.

It appears that an increase in depth of needle penetration increases the number of fibres which are reoriented during a single needle insertion. At low penetration reoriented fibres remain in the loop form as they are released from the needle at its lowest point before any breakage occurs. As penetration increases more barbs enter the web and thus more fibres are either attached to the barbs, or become involved with those which are, causing increased reorientation.

The importance of needle variables barb size and number of barbs (which interacts with depth of needle penetration) is obvious. In normal needle production barb size is proportional to blade gauge, and thus with all else constant it is to be expected that an increase in blade gauge will cause more fibres to be reoriented.

(c) <u>Influence on horizontal structure</u>

It has been explained how various web and machine parameters determine the size of individual reorientation points within needled fabric. The size of the vertical fibre tufts governs the amount of distortion applied to fibres in the horizontal web plane during needling and thus affects fabric horizontal structure, as does the frequency of these re-orientation points. Thus from what was shown earlier the use of low needling density or high penetration increases the distortion suffered by fibres in the horizontal plane.

Other factors affecting horizontal structure are:

1) needle arrangement in the loom
2) fibre orientation in the card web

The more obvious effects of fibre orientation on horizontal structure have been mentioned, but the difficulty of characterising card web structure and the arrangement of punching points in the fabric limits the precise information available and obtainable on needled fabric horizontal structure. Photographs showing the effect of needling on card web horizontal structure have previously been presented.(8).

4. Mechanical Properties of Needled Felt

The properties of a textile product are closely related to its structure. In the case of needled fabric factors which affect the precise structure obtained by the needling operation have been discussed in the previous section; it follows that these same factors will influence the properties of the fabric produced. The majority of published work in this area (11,12,13) has been concerned with the variations in fabric tensile properties which can be obtained by alteration and combination of different web and machine parameters; the present discussion will consider this information with comment on how the same factors could influence the ballistic resistance of needled felt.

(a) Load-elongation characteristics of needled felt

When needled fabric is subject to a uniaxial tensile test at constant rate of elongation (as on Instron Tensile Tester) a trace such as shown in Fig. 3 is obtained. This shows the S-shape typical of needled material and can be explained as follows. Initially there is low resistance to straining due to easy straightening of fibre slackness and curl and the generally disordered nature of the unstretched fabric; hence the low initial modulus characteristic of this material. On further extension the curve steepens as fibres are pulled into a tightly packed structure. This is a self locking mechanism with further extension taking place through intermittent slippage. Finally near the rupture point extension again becomes easier presumably due to fibre breakage. The extent of the stick-slip pattern is dependent on fibre frictional characteristics and its presence indicates the importance of slippage during needled fabric breakdown. Once fibres have been aligned during initial fabric extension, inter-fibre forces build up to restrict further extension and stresses develop within the fabric. When these stresses are sufficient to overcome the inter-fibre forces slippage occurs with a consequent drop in load on the fabric. Immediately the load rises as inter-fibre forces build up again between fibres in their new positions, and in this way the stick slip pattern is formed. The increase in frictional contact as the structure becomes tightly packed is illustrated by the increased amplitude and reduced frequency of the oscillations as the rupture point is approached. In this region fibres will stick for a longer period before slippage can take place.

It has been possible to show (17) certain general effects of a uniaxial tensile test on needled fabric structure. On initial extension adjacent vertical pegs are pulled closer together by the straightening and alignment of fibres in the fabric horizontal plane. Subsequent extension produces a locked structure in which the tufts are compressed into elliptical form along the direction of test. This is the point at which fibres in the horizontal plane must begin to slip. Lateral contraction of the fabric takes place and groups of pegs are consequently drawn closer together across its width. Thus the low initial modulus of needled felt is due to the straightening of fibres which takes place during initial extension. When fibres in the horizontal plane are packed tightly against the vertical tufts causing their compression, stress is built up in the fabric and the load-elongation curve rises steeply. Breakdown occurs when the stress generated within the fabric by extension cannot be sustained by the inter-fibre frictional forces, and takes place through a combination of fibre breakage and slippage. Variations on this general deformation pattern have been proposed (17) for fabric made using different values of needling density and depth of needle penetration.

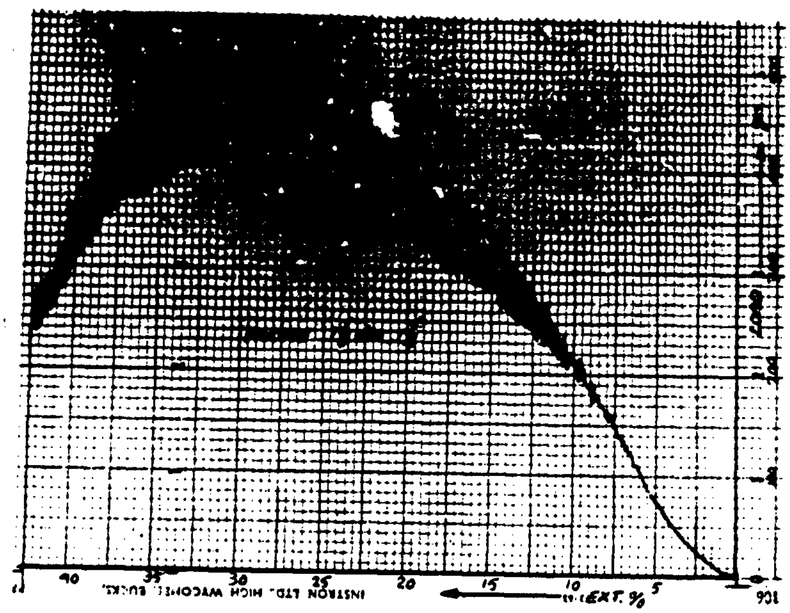
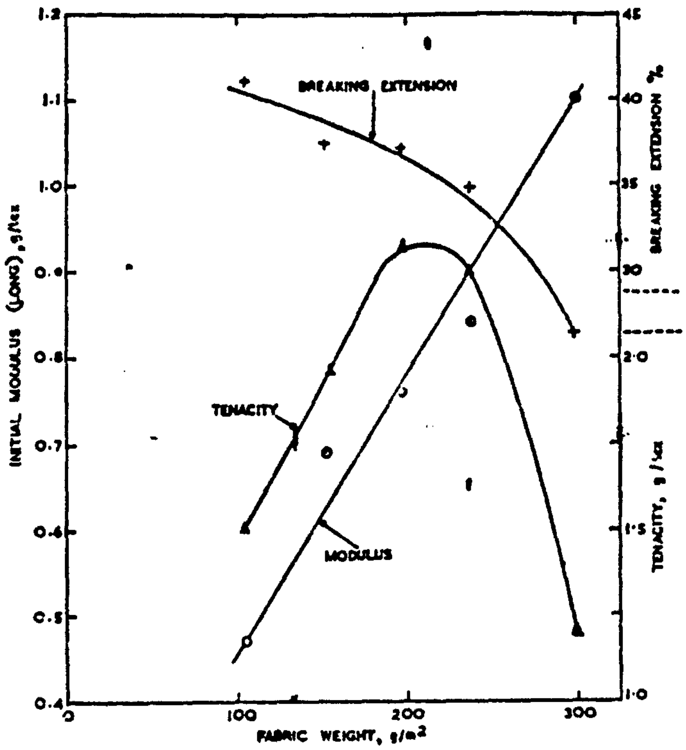


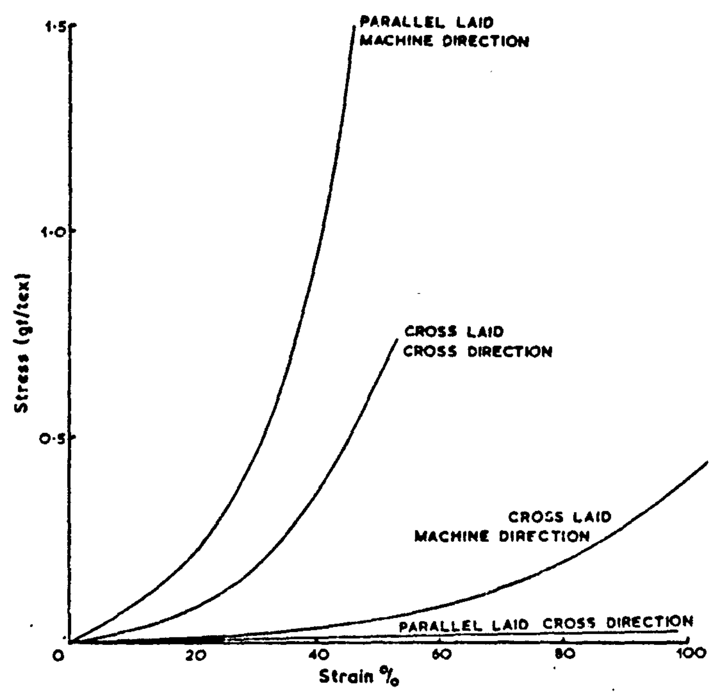
Figure 3

TYPICAL LOAD-ELONGATION CURVE FOR NEEDLED FABRIC



Variation of tensile properties with fabric weight (viscose rayon, 2½ in., 3 den; 240 needles/in², ½-in. penetration)

Fig.4.



The Effect of Fibre Orientation in the Web on Fabric Stress-Strain Curve.

WEB WEIGHT 568 g/m²
FABRIC WEIGHT { PARALLEL LAID 468 g/m²
CROSS LAID 462 g/m²
NEEDLING 240 punches/in²
PENETRATION 1/2 in.

Fig. 5

This is the general pattern of needled fabric behaviour during a uniaxial tensile test illustrating the various mechanisms involved. It has been shown (3) that the load-elongation curve of needled fabric is virtually independent of strain rate, and thus it is reasonable to assume that these same mechanisms will play some part in fabric deformation during high speed transverse impact.

(b) Effect of various parameters

1. Web Weight (10,17,18)

The influence of web and hence fabric weight on needled fabric mechanical properties is difficult to isolate because of its close interaction with the machine parameters of needling density and depth of needle penetration. For a given fibre type and dimensions an increase in web weight is achieved by an increase in web thickness and thus for a given depth of needle penetration more of the needle enters the web during punching. Thus more barbs may enter the web causing increased fibre reorientation, and in addition fibres picked up from the web surface by the first barbs on a needle travel a greater distance during a single penetration. This may increase the level of fibre breakage within a fabric. Both these factors would have a definite effect on the properties of the resultant fabric.

A systematic study designed to isolate the influences of web weight needling density and depth of needle penetration on fabric mechanical properties has not been carried out but some general comments can be made.

Fabric tenacity increases with web weight up to a maximum value with a subsequent decrease above an optimum weight. This weight is governed by the machine parameters; for instance, high needling and depth of penetration will induce the strength reduction at a lower web weight than if less drastic needling parameters are employed, but may give better fabric properties before this optimum is reached.

There are two reasons why fabric tenacity will decrease above an optimum value of web weight:

a) so many fibres are reoriented into the vertical fabric plane that few are left in the horizontal plane to build up inter-fibre forces to resist straining. This case applies when using high values of needling density and depth of needle penetration at low web weights.

b) as mentioned earlier, when reoriented fibres from the web surface are pulled a greater distance through the web because of an increase in web thickness much of the contact between the horizontal and vertical structure is destroyed and this is essential for the realisation of maximum strength from a needled structure. This mechanism will eventually occur with any combination of needling parameters as web weight is increased.

Fabric initial modulus increases with web weight because with a greater number of fibres in the vertical plane larger forces are developed by fibre straightening and alignment during initial extension.

Fabric breaking extension reduces with web weight regardless of machine parameters employed. This is initially due to restrictions on fibre movement in the horizontal plane caused by the increased number of reoriented fibres at higher web weights, and subsequently (past the web weight giving maximum fabric tenacity) due to fibre breakage reducing the amount of extension necessary to cause fabric breakdown.

The effect of web weight on fabric tensile properties at fixed values of needling density (240 punches/sq.in.) and depth of needle penetration (½") for fabric made from viscose rayon (2½" 3 den) is shown in Fig. 4. (after Hearle & Sultan (10)).

In the case of ballistic resistance the effect of web and fabric weight will be different. This is because felt for ballistic purposes is employed in unattached layers and thus optimum tensile properties can be achieved in individual layers and the required thickness made up by a combination of these layers. The foregoing discussion will be applicable to the tensile properties of individual layers which in themselves should not be too thick or free response of the whole to impact will not be obtained.

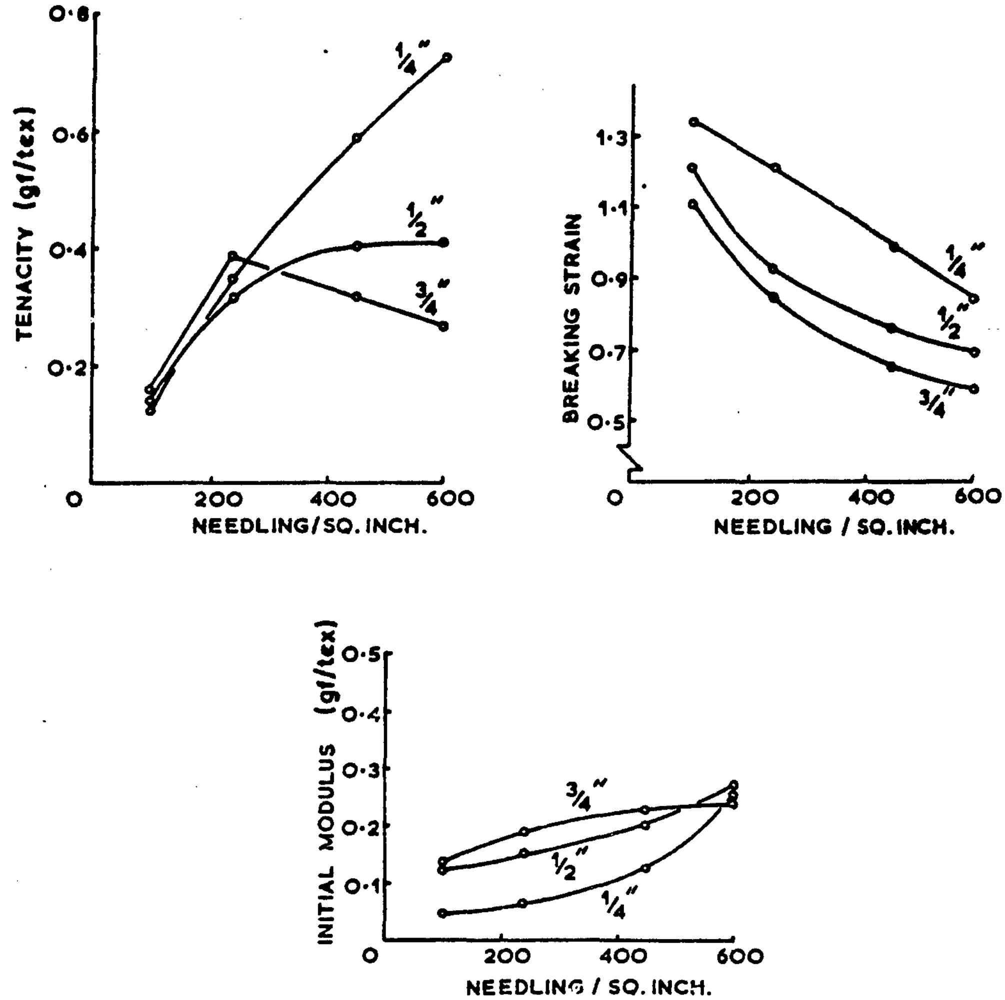
2. Web Structure

The stress-strain curves for parallel and cross laid fabric made from the same web weight, fibre type and dimensions, and under the same production conditions are shown in Fig. 5. It is seen that although the parallel laid fabric is much stronger in the machine direction, because the majority of fibres lie in that direction and can contribute directly to strength, its cross-wise strength is very low. A greater all round strength as is required for transverse impact is obtained by using cross-laid material in which a greater range of fibre orientations is present. Under transverse impact parallel laid material will split along the machine direction because the cohesive forces between fibres across the fabric width are low.

3. Web composition

As slippage is largely responsible for the deformation of needled fabric, fibre frictional characteristics will play an important part in determining resultant fabric strength (12). This has been recognised and work carried out to modify fibre frictional characteristics to improve ballistic resistance (3) and the uniaxial tensile properties of needled fabric (14).

The importance of individual fibre tenacity in determining fabric strength is not understood in detail, although needled fabric is one textile structure in which the first approximation to the fabric stress-strain curve is that of the constituent fibres (9). Fibre tenacity is an important factor during the actual needling process since the use of weak fibres would lead to excessive breakage during reorientation.



The Effect of Machine Parameters on Needled Fabric Tensile Properties.

Cross laid web (340 g/m²)

Fig. 6.

From the ballistic protection standpoint it appears that increased fibre tenacity improves fabric resistance (3).

As fibre dimensions govern the extent to which frictional characteristics can be utilised within a fabric they are of primary importance in determining fabric strength. Hearle & Sultan (13) have shown that with all else constant longer fibres produce stronger needle punched fabric. This is because higher inter-fibre frictional forces can be generated along their lengths to resist slippage. It is important to note that although a given fibre length is stipulated as having been used to produce a particular needled product, breakage occurs during carding and needling and thus the average length of fibres present in the fabric is probably only half the original; depending on the values of machine variables employed. Thus if longer fibres are used initially more breakage is acceptable during processing before fabric strength declines.

If fine fibres are used during needling breakage will occur, but can be reduced by the use of finer gauge needles or fewer barbs. On theoretical grounds it is to be expected that stronger fabric will be produced by using fine fibres because higher frictional forces can be built up. [The analogous case for staple fibre yarns has been explained by Hearle (19)]. This might explain the improved ballistic resistance shown by decreasing the denier of modacrylic fibres used in a needled felt.(3).

4. Needling Density

The effect of needling density on fabric properties is dependent on the web weight and depth of needle penetration employed.

As increased needling increases the number of reorientation points within the fabric, larger forces are built up during initial extension (giving increased values of initial modulus) and there is greater resistance to slippage throughout extension (increased fabric strength). As fibres become locked together more quickly during extension breaking strain values decrease with increased needling density. However for any combination of web weight and needle penetration values there is a limiting needling density above which excessive fibre breakage occurs producing fabric breakdown.

5. Depth of Needle Penetration

The combined effects of this factor and needling density on a cross-laid web of weight 340 g/m^2 are shown in Fig.6. It is seen that even at the highest needling density employed fabric tenacity is still increasing at the lowest penetration. In this case strength is being maintained by small vertical tufts because there is a high level of contact between the horizontal and vertical structure. Excessive penetration destroys this contact and even though larger tufts are produced fabric strength falls. Thus high strength fabric can be produced by using high needling density and low penetration; however, if web weight is too high low needle penetrations will cause the resultant fabric to be bulky and consequently difficult to handle and make up.

For ballistic purposes fabric should be flexible, but if the web is not securely held together breakdown will occur during transverse impact due to fibres being drafted from the fabric. Thus compromise values of these needling parameters must be used. It seems probable that low needling density and high penetration would be most suitable for this purpose.

6. Needle Variables

The type of needle used during fabric production is governed by the type and dimensions of fibre in use. For instance low denier fibres require fine gauge needles, whereas bulky fibres would probably be best needled with heavy gauge needles making use of the larger barbs. The wrong use of needles will cause a deterioration in fabric tensile properties due to fibre breakage. Some basic rules for needle selection have been published (20).

(c) Recovery characteristics of needled felt.

Another mechanical property of needled fabric possibly relevant to its ballistic protection capability is the ability to recover from applied extensions. The effect of various parameters on this property have been reported and will be mentioned here.

Hearle & Sultan (10) have shown that recovery decreases with extension owing to fibre slippage. At very low strains a period of increased recovery was sometimes observed due to fibre straightening and alignment in the unstretched fabric, but as slippage becomes pronounced recovery decreases. In general recovery is poor and at 10% ext. is of the order of 20% for a viscose fabric, decreasing with increased fabric weight.

Wool fabrics made at ½" penetration were tested (11) and showed increased recovery as needling density was increased. This occurs because at higher needling densities more fibre straightening is necessary before slippage can occur.

Fibre properties are important in determining fabric recovery (13), Courtelle and wool fabrics giving much higher elastic recovery than rayon fabric. This reflects the better recovery properties of those fibres as opposed to viscose. In addition viscose fibres are more easily consolidated during needling and this may hinder recovery.

(d) Conclusions

The object of this chapter has been to review the present state of knowledge on the structure of needled felt, and the variation of fabric mechanical properties with web and machine parameters.

Although the reaction of needled material to high speed transverse impact at the point of collision may not follow a simple stress-strain curve, fabric forming the surface of the deformation cone will in some part be subject to mechanisms similar to those described here as energy absorption takes place through fibre straightening, alignment and slippage.

CHAPTER III

BEHAVIOUR OF NEEDLED FABRIC SUBJECT TO TRANSVERSE IMPACT

1. Introduction

Initially a slow speed test was employed in an attempt to study the mechanism of deformation during the transverse impact of needled felt. Subsequent testing involved the use of relatively high speed projectiles fired from a fixed velocity air rifle. High speed ciné photography has been used to study the deformation process, and sections cut through pieces of impacted fabric have provided information on the response of individual layers within a multi-layer system.

2. Fabric Manufacture

Cross-laid web was utilised throughout this investigation as preliminary tests had shown that the necessary all round fabric strength was not possible when parallel laid material was employed. The needle loom was a Bywater Model KN. This loom operates at 240 punches per minute (industrial machines usually operate at three times this speed) and has a needle board containing 550 needles facilitating the easy and relatively quick changing of needles for experimental purposes. It has previously been found satisfactory for the manufacture of fabric for testing purposes.

Unless otherwise stated fabric was manufactured at 250 punches/sq.in and ½" penetration (using needles 15 x 18 x 32 x 3, 9 barbs), the resultant weight being 12.5 oz/sq.yd. Viscose rayon fibre (2½" 3 den) was commonly used, fibre type being considered unimportant when considering deformation mechanisms in general.

3. Slow Speed Test.

(a) Method of Test

Ehlers and Angelo (5) concluded that their particular form of slow speed test did not produce results which correlated with V_{50} figures. However, if a piece of fabric (4" x 2") is allowed to freely deform when contact with a steel rod occurs, a mode of deformation comparable with that resulting from high speed fragments occurs; an area of fabric in the vicinity of the penetration point taking on a conical shape. The experimental arrangement is illustrated in Fig.7. As no means of checking measured loads against V_{50} values was available at this stage of the investigation, only the nature of the load-penetration curve recorded during this slow speed testing was regarded as of interest. More extensive comparative studies would be appropriate when a V_{50} or similar test was also carried out.

(b) Pattern of behaviour.

At a cross head speed of 2 cm/min the Instron was sufficiently sensitive to record detailed variations in load as the probe passed into the fabric. Such a curve is shown as Fig. 8, and it is seen to be largely composed of stick-slip oscillations as is the case when needled fabric is extended in a uniaxial tensile test [Fig. 3].

The pattern of this recorded behaviour can be explained as follows. Initial contact between probe and fabric causes fabric compression and a consequent steady increase in load. Eventually fabric extension in the transverse direction reaches a level at which fibres begin to slip, resulting in a momentary drop in the load level which the fabric is capable of sustaining. Immediately fibres become gripped again in their new positions and the load rises. The increase in amplitude of the oscillations near the fabric breakdown load suggests that final fabric failure occurs when transverse extension is such that regripping of fibres becomes increasingly difficult until eventually they separate allowing fabric rupture.

Thus it seems that mechanisms similar to those apparent during uniaxial straining are in operation during a transverse impact test. This is not surprising as any permanent deformation of needled fabric must involve fibre slippage.

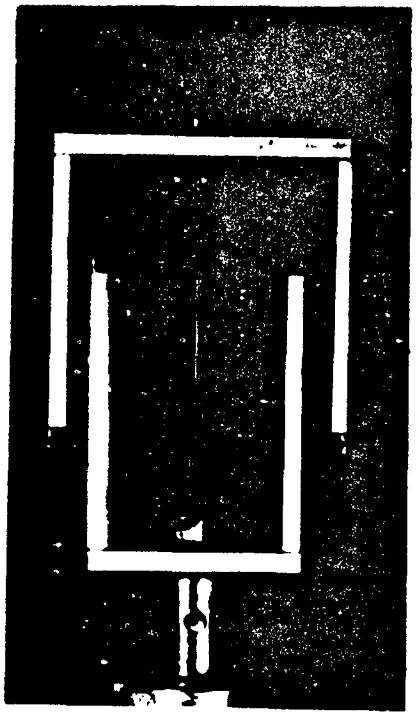
(c) Fabric deformation

An embedding and sectioning technique which has been used in this laboratory (8) to investigate the structure of needled fabric was adopted to study the deformed material. A similar method has been used in the study of woven fabric subject to transverse impact (21). So that the behaviour of fibres could be studied during the deformation process, several layers of coloured fibrewere placed on the surface of the white prior to needling. Pieces of this fabric were then subject to a series of increasing loads using the Instron test method. An area sufficient to include all that affected by the penetration process was cut from each fabric and set in Araldite resin. From the resultant block of resin and fabric, sections were cut through the cone of deformation using a mechanical saw. The sections were ground and polished with varying grades of emery paper and are as shown in Fig. 9. In this case the fabric was subjected to transverse loads of 5,10 and 20 kg, and it can be seen that as the load increases so does the base length of the deformation cone as more of the fabric becomes involved in an attempt to restrict probe movement. Fabric vertical structure is only distorted in a region close to the impact point and fabric thickness has been reduced in this area, possibly due to extension. Around the point of impact fibres have been plucked from the fabric surface and dragged along in the path of the steel rod as extension has occurred.

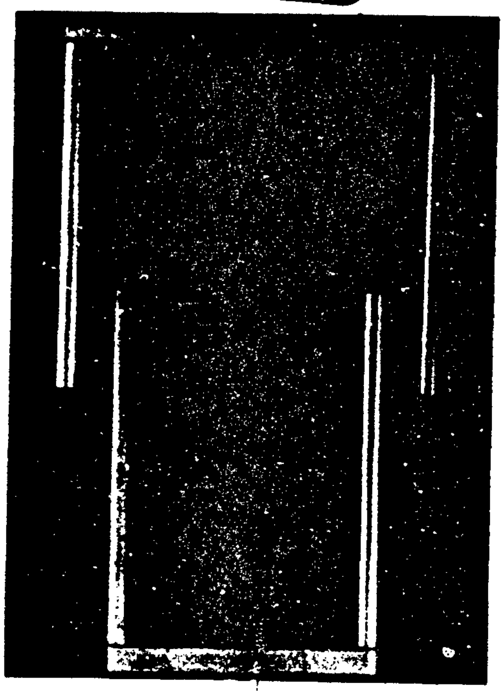
The object of this preliminary study into needled fabric transverse deformation has been to show that fibre slippage governs fabric deformation in the same manner as with uniaxial extension. It is also seen that deformation is not restricted to the immediate area surrounding the point of impact but affects an area the radius of which increases in size with fabric extension.

4. High Speed Testing

As no facilities for true V_{50} testing were available, the study of fabric deformation was continued by using a free flight projectile fired from a fixed velocity air rifle. The projectile employed was a waisted lead pellet of weight 1 gm fired with a velocity of 534 ft/sec. Circular fabric specimens of six inches diameter were held in aluminium frames mounted rigidly in a rack capable of holding three such frames, the centres of the specimens coinciding with the projectile path. In this manner it was possible, when required, to slow down the projectile by passage through an initial specimen and to study the deformation of subsequent fabrics.



(a) Before Impact.



(b) During Impact

Figure 7

SLOW SPEED PENETRATION TEST ON INSTRON

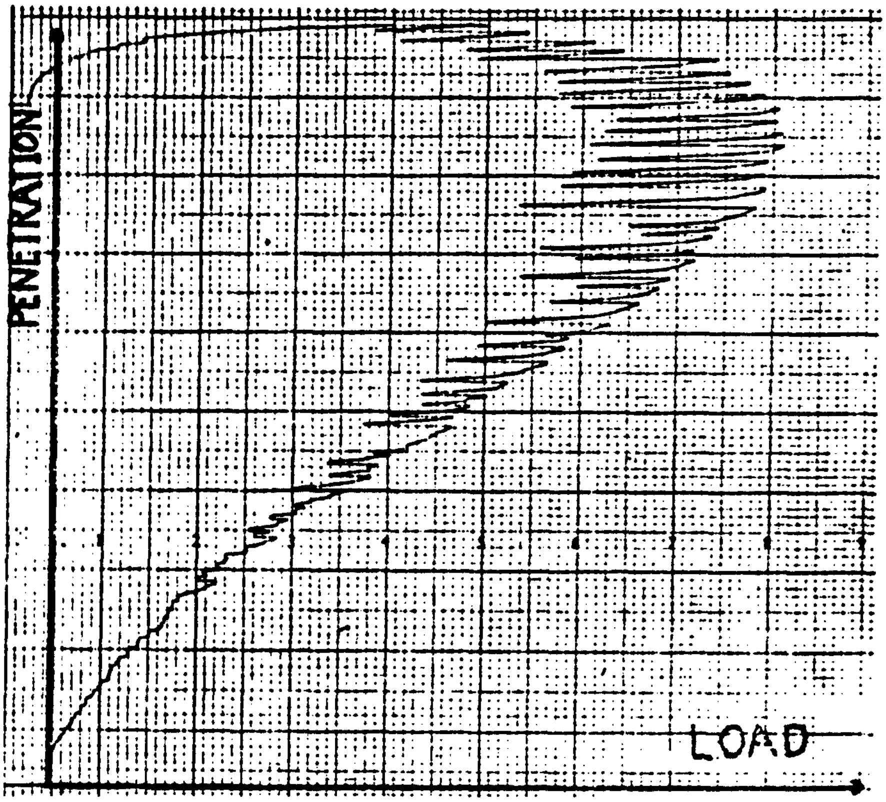


Fig.8. Load-Penetration Curve during slow speed test.

Fig.9. Fabric Sections from slow speed test.

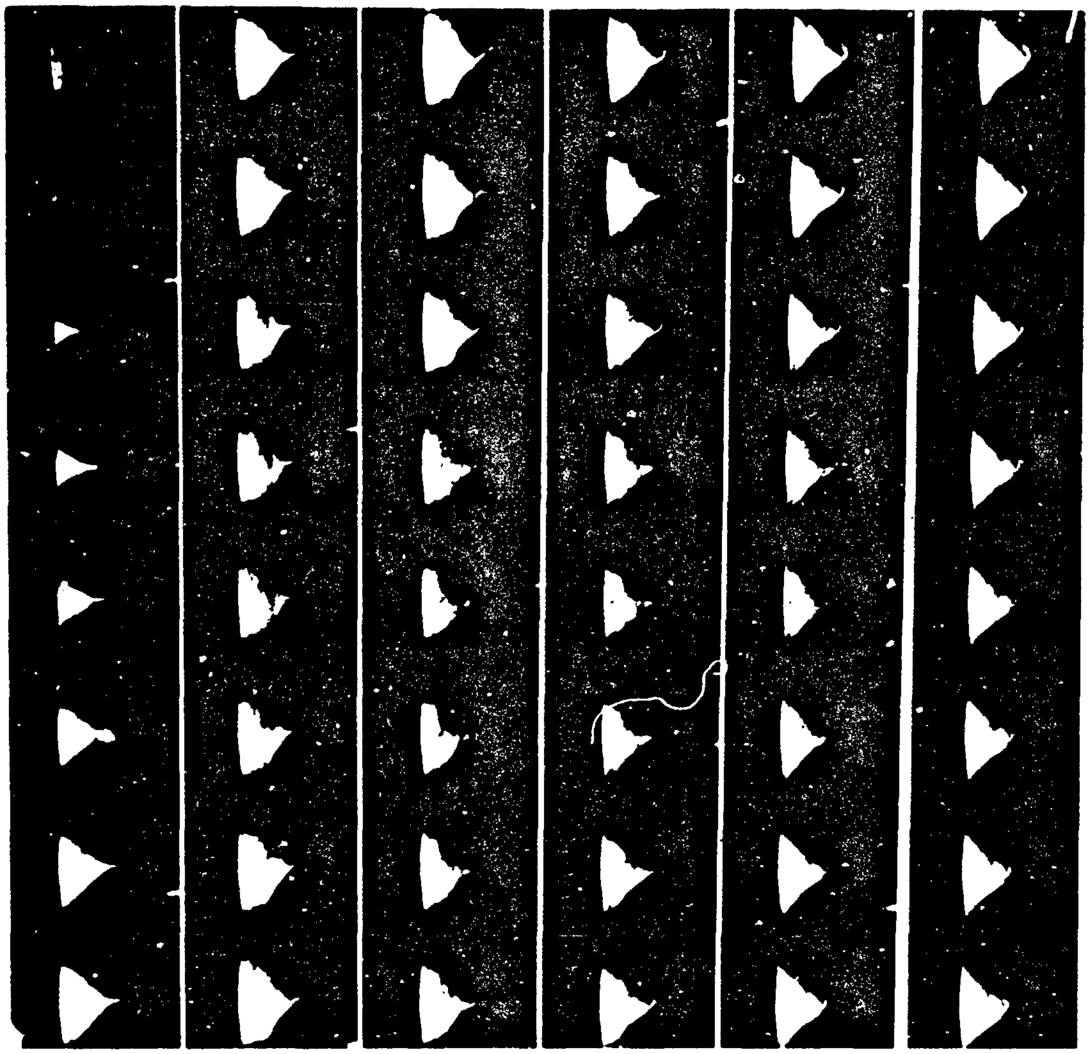


Figure 10

FABRIC PENETRATION

Although the maximum possible projectile velocity was less than that required to test the suitability of fabric prepared under the military specification, by reducing the thickness of fabric tested realistic behaviour can be observed.

Study of the deformation process took the form of high speed ciné photography using a Fastax camera capable of running speeds up to 9000 frames/second. The speed found suitable for and utilised in the present study was around 5000 frames/second.

In most instances fabric deformation was studied from a position at right angles to the axis of projectile travel. However, to study more closely the apex of the cone of deformation, the steel buffer plate against which projectiles were stopped was replaced by a sheet of bullet proof glass. In this manner photography could be carried out along the axis of the projectile path or at a small angle to it.

Various phenomena apparent during deformation are shown by these films . Sections from the most important will be presented here and the evidence discussed within the next chapter.

(a) Fabric penetrated

Figure 10 is a sequence of film showing the penetration of a single layer of the fabric whose manufacture was described in section 2 of this chapter. The pellet apparently leaves the fabric in frame 4 after impact, with an attendant tail of fibres protruding from the fabric. Up to this point transverse fabric deformation had occurred in the form of a cone, the base of which increases in diameter with extension. After the pellet has emerged maximum extension in the transverse direction is reduced, but fabric occupying the whole six inch diameter circle moves forward to some extent. As initially the specimen was held under slight tension within the frame this must mean that the whole fabric is under strain absorbing the energy transferred from the projectile during their brief contact. Subsequently as the energy is dissipated some fabric relaxation occurs.

(b) Projectile stopped

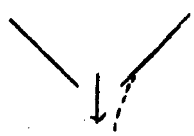
The sequence shown as Fig 11 depicts the same impact process as in Fig. 10 (i.e. same fabric in use) except that the projectile had been showed down an undetermined amount by passage through a piece of needled felt, placed three inches in front of the test specimen.

In this case the pellet approaches the fabric surrounded by fibres removed from the initial specimen (this suggests the possibility of a breakthrough mechanism in which a tuft of fibres is pulled from the fabric). The impact process follows the same pattern as previously in that a maximum transverse extension is reached and subsequently the whole fabric area expands outwards. In this case the pellet did not emerge, and recovery is such that the fabric began to turn inside out.

From the film sequences shown in Figs 10 and 11 it appears that transverse fabric extension, in the form of a cone, takes place until either a projectile is defeated or emerges from the fabric. The energy thus absorbed from the projectile is then dissipated within the fabric as a whole causing a reduction in maximum extension.

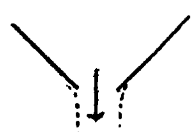
(c) Final fabric breakdown.

In the fabric which was penetrated, final breakdown occurred by the pulling out of one arm of the loop of fibres which surrounds the pellet during impact. This suggests weakness in the fabric, more useful material should give a uniform deformation in the breakthrough area. The observed mechanism is depicted in (a).



(a)

At least one other mechanism of fabric breakdown has been noted and is seen in figure 12 and in (b).



(b)

In this case it appears that the area in close proximity to the impacting missile has been stretched until breakthrough has occurred by means of fibre separation by slippage. The two arms of the separated 'loop' are clearly seen.

One other phenomenon which was observed on projectile emergence is fibre breakage. In the sequence shown as Fig.13 pieces of broken fibre are seen as the pellet breaks through. It is not suggested that fibre breakage is a major source of failure in needled fabric during transverse impact, but that it may accompany other mechanisms particularly if fibre movement is restricted in some way. It is also possible that broken fibres may have existed within the fabric, having been caused by the needling operation, and be released by impact.

(d) U.S. Army needled nylon fabric.

For a more systematic study of needled fabric deformation, pieces of nylon fabric (10.5 ozs/sq.yd, platen pressed) supplied by Natick Laboratories were tested.

The deformation of a single layer of this fabric is shown in Fig. 14. It appears that the projectile emerges by stretching the fabric until extension is such that no further resistance is possible.

When a specimen consisting of two unattached layers of this fabric was fired much greater extension, about one inch greater than for a single layer, is achieved. In this case (Fig.15) the pellet is stopped, and it is seen that the main cone of deformation is stretched into a cone of much smaller radius surrounding the pellet. High localised fabric extension has occurred in this region. This specimen recovered violently and ultimately turned completely inside out due to the absorption of all the projectile energy. Neither layer was penetrated by the projectile and yet the first layer had extended further than during the single layer test. This illustrates the influence of the back up layer which prevented breakdown.

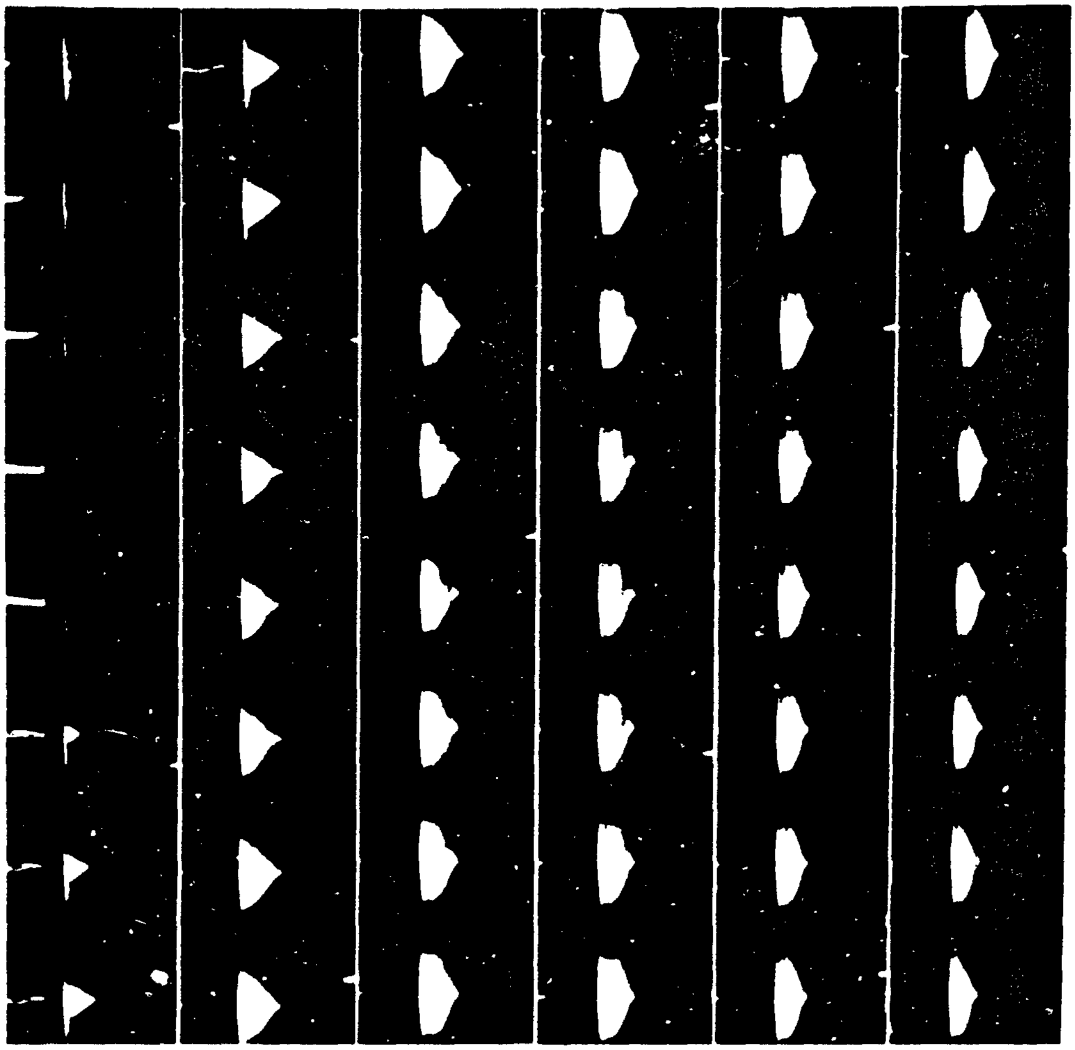
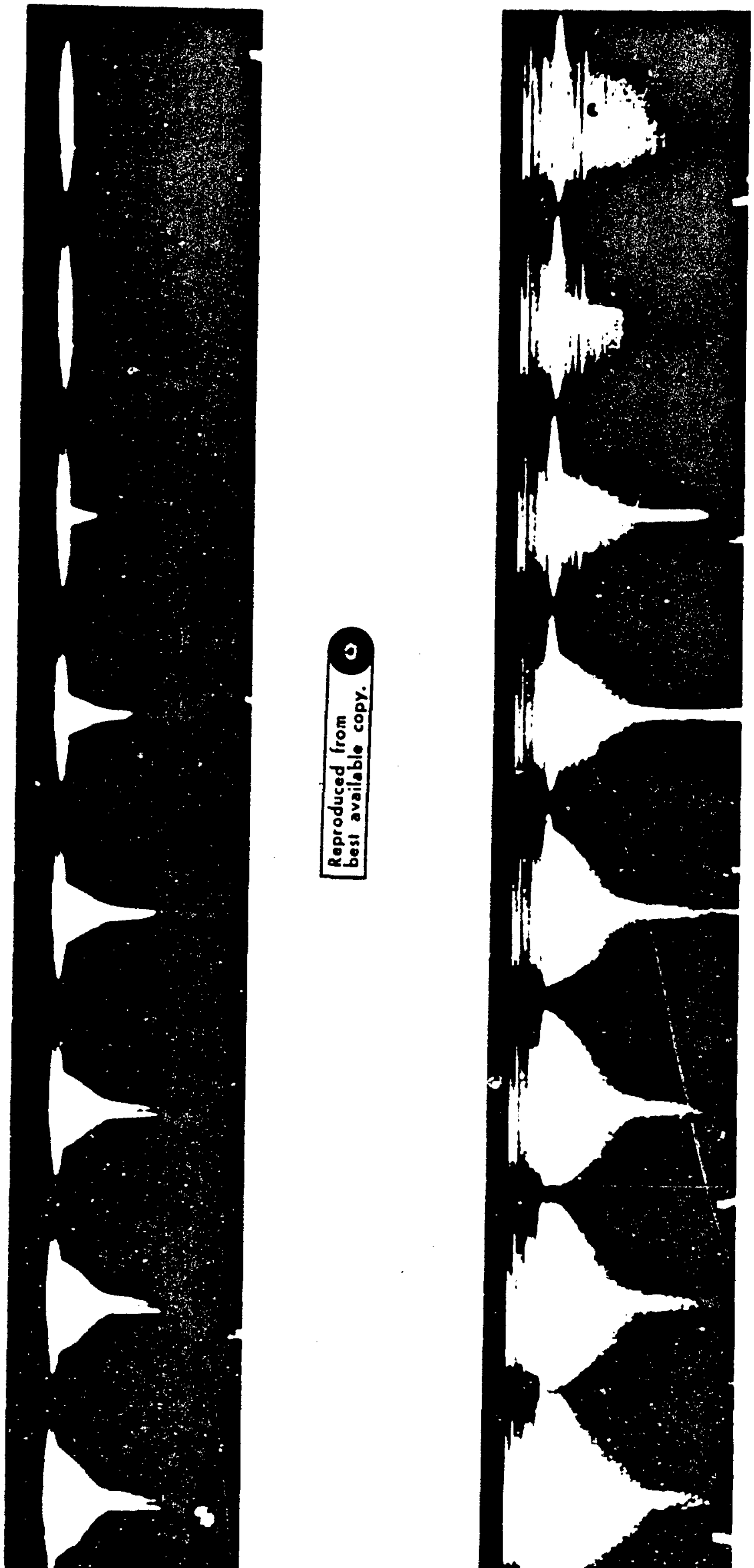


Figure 11

PROJECTILE HALTED



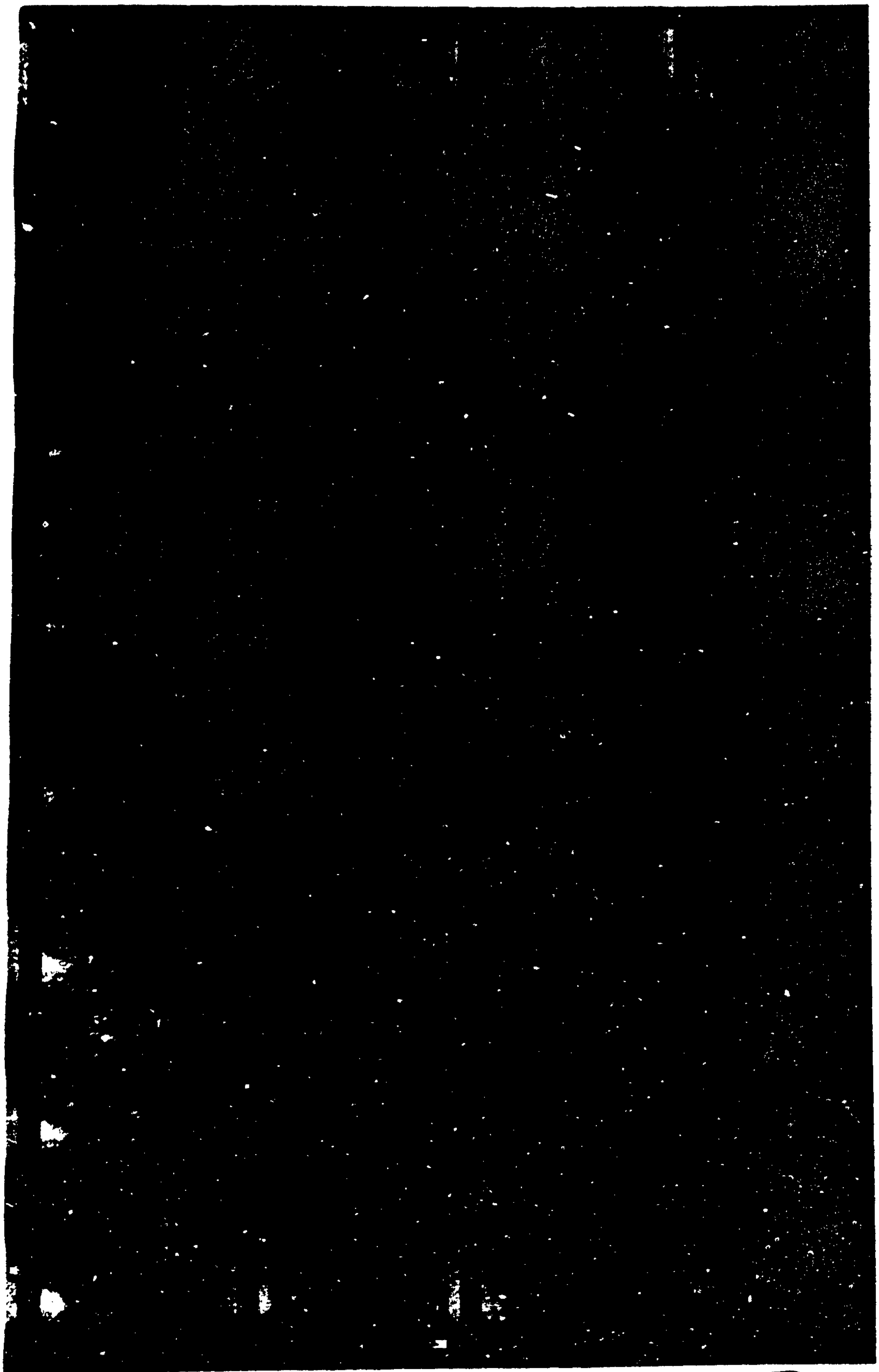


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Figure 14

SINGLE FABRIC LAYER

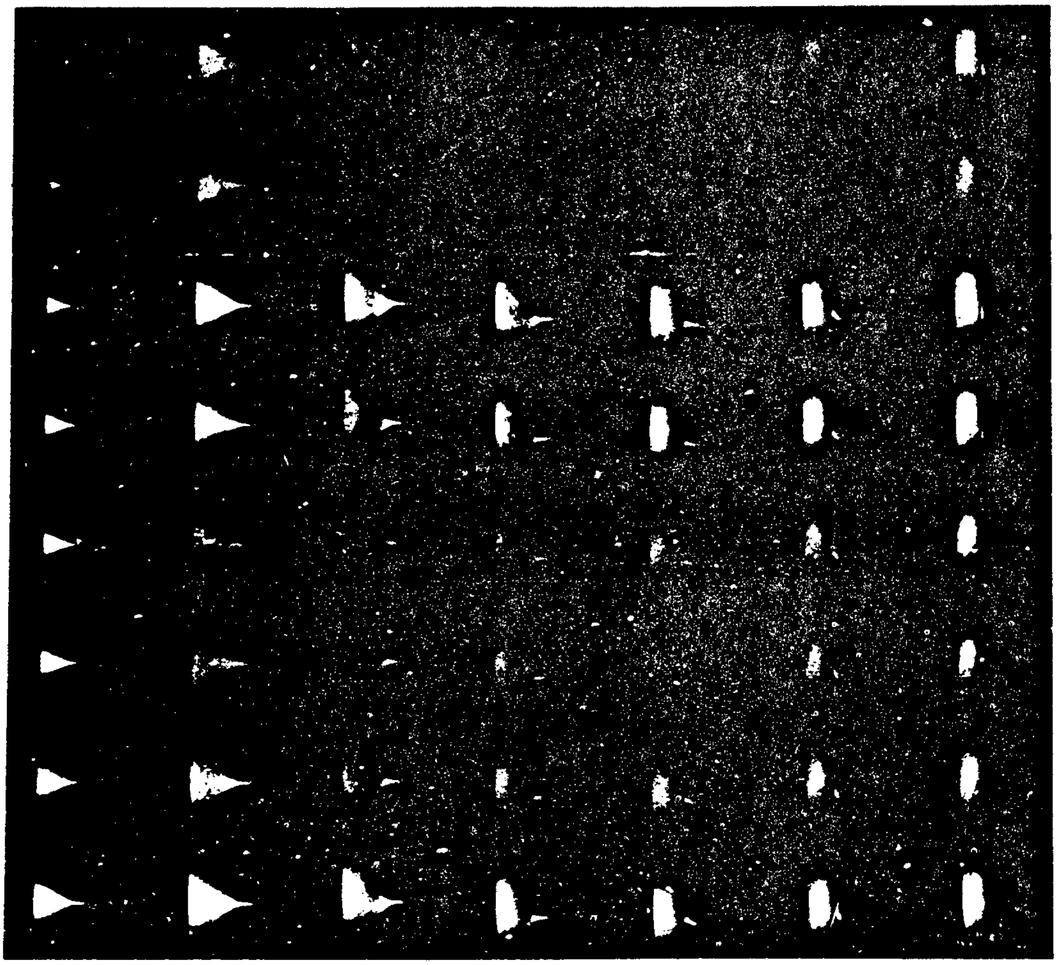


Figure 15

DOUBLE FABRIC LAYER

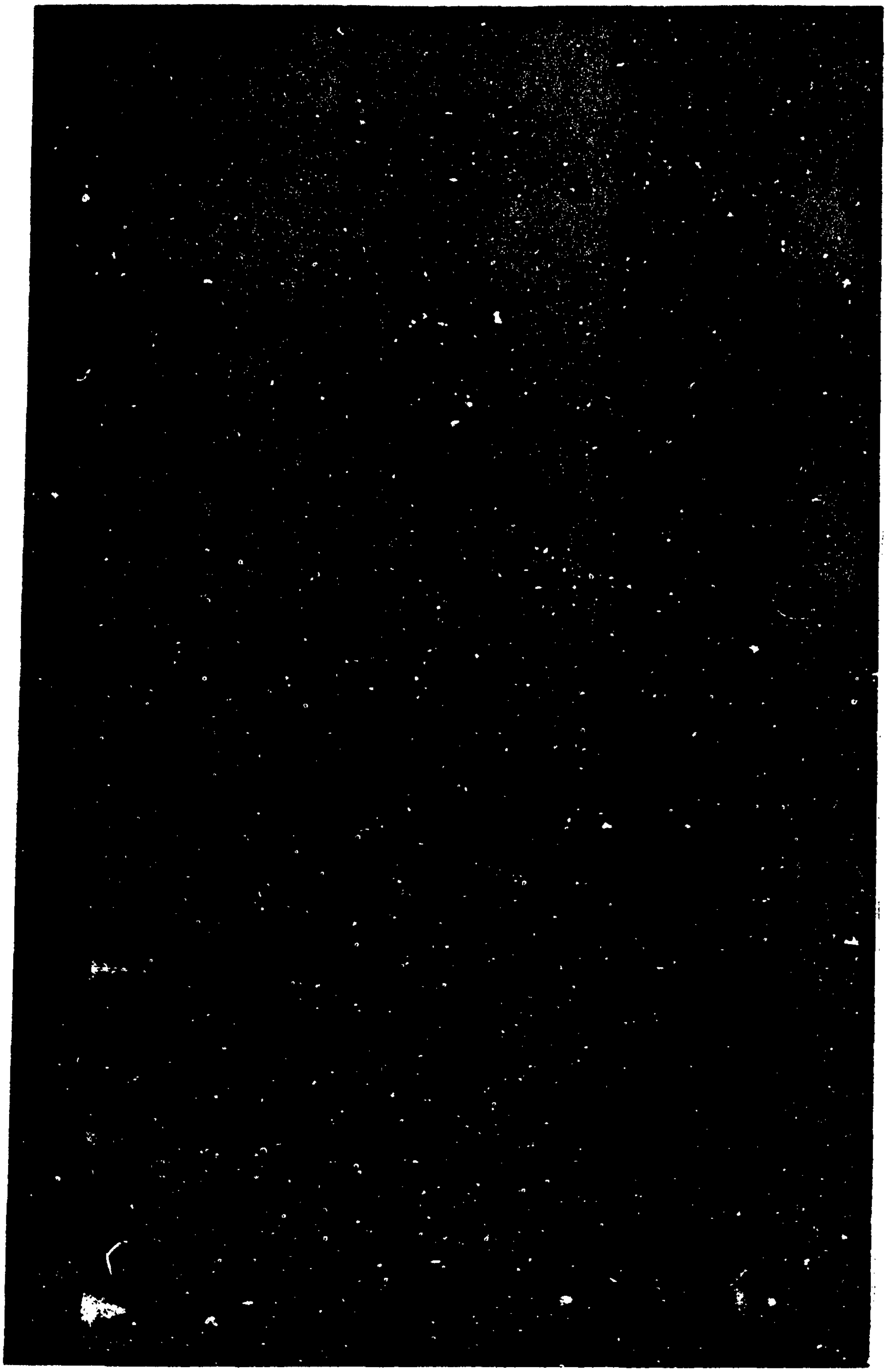


Figure 16

FOUR LAYER SPECIMEN

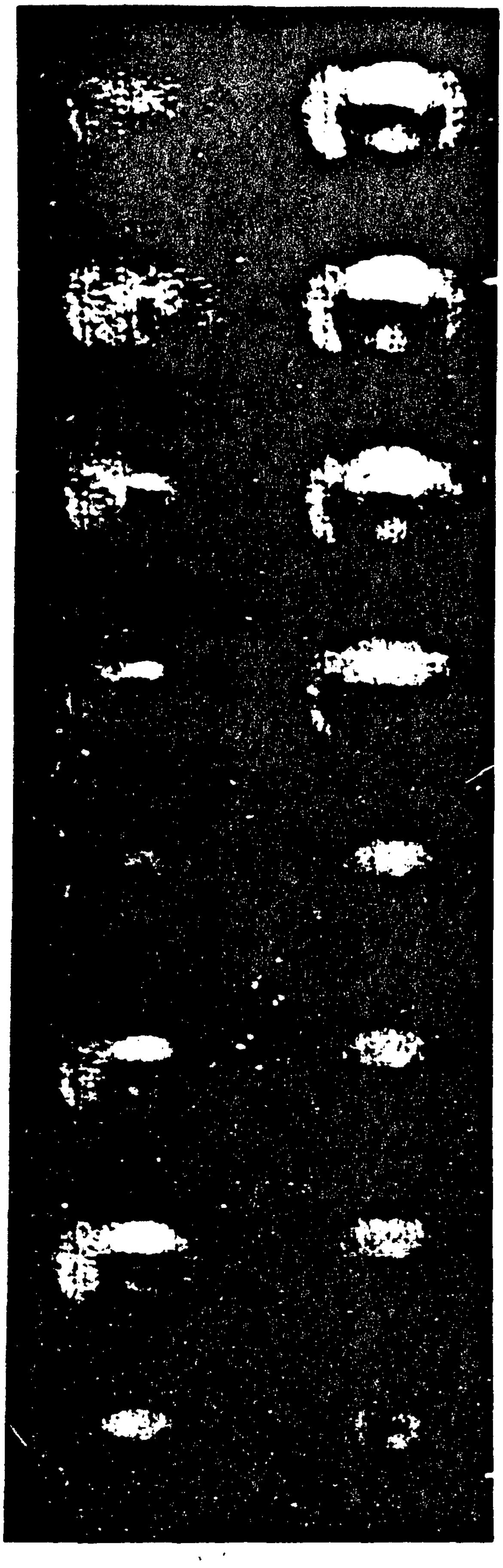


Figure 17

Figure 18

When the specimen thickness is increased to four layers the pellet is halted more easily. Fig.16. Fabric extension is the same as in the single layer case and undue stresses are not placed on the area around the impact point. As energy absorption takes place over a larger fabric area, recovery behaviour was not as drastic as in the two layer case, when it is probable that the projectile was only just prevented from penetrating.

These films show that using the lightest fabric possible to stop the projectile produces excessive fabric extension. An increase in this weight provides resistance against projectiles of higher velocity and also reduces the extension which occurs whilst stopping projectiles in the lower velocity ranges. Any reduction in the cone height during deformation will make needled fabric of more practical use, but means should be found for achieving this other than by a weight increase.

(e) Projectile axis photography.

The steel buffer plate placed at the end of the specimen holder rack to stop emerging pellets was replaced by a piece of bullet proof glass. Deformation could now be viewed along the fabric axis or at a slight angle to it. This allows the whole fabric surface to be viewed during impact.

One interesting photographic sequence obtained by this means is shown as Fig. 17. The fabric tested was made from a web which had a surface of red fibres. On needling some of the red fibres were pulled through the web and show on the base. The needling lines produced can be seen on the film (a diagonal needle arrangement was used to make this fabric resulting in these straight lines of needling along the machine direction - better fabric is make using a more 'randomised' arrangement of needles). It is observed how this line moves inward towards the point of impact but as the base of the deformation cone enlarges and meets the line its direction changes and it moves outwards. This behaviour is in accordance with previous observations (4) made using the spark gap technique, which showed how the fabric initially moved inwards due to the inward radial velocity imparted to the felt by the longitudinal tensile wave, and subsequently reversed direction due to the action of the transverse wave.

A sequence of film taken with the camera at a slight angle to the projectile axis is shown in Fig 18. In this case the pellet was sprayed a black colour to make it more clearly visible. The fabric under test was a single layer of the nylon material previously discussed. The photographs show that the projectile emerges during the third frame of deformation, before the cone has spread over a wide area, although its localised extension is considerable. It seems that the pellet has passed through the apex of the cone by extending it to such a degree that separation of the fibres has occurred.

5. Fabric Sections.

A further method of studying fabric deformation under impact is by means of the embedding and sectioning technique used to produce Fig. 9. This can only be applied to fabrics which are not penetrated by projectiles as any loose fibre produced by total breakdown would be distorted during the embedding process. For this study fabric was used with coloured fibre surface layers so that the deformation could be more clearly seen in the resultant sections.

The sequences of high speed ciné film previously shown have indicated the changes which occur in fabric between the point of maximum extension and when the samples become stationary. Fabric deformation during an unsuccessful penetration is considerably greater than appears from the fabric after testing; this must be taken into account during interpretation of these results.

Fig. 19 shows cross-sections through single, double and treble layer fabrics after impact. Fig 19 (a) shows part of the deformation cone (each sample was originally six inches in diameter) of a single piece of fabric struck by a projectile which had previously been slowed down by passage through another piece of similar material. (In this case the coloured fibre layers are in the middle of the fabric) Fig 20(b) shows the effect of impact on a double layer of fabric. One problem with the application of the embedding technique in this instance is the possibility that resin will not penetrate completely to all parts of the sample, leaving holes in the sections and making good photographic reproduction more difficult. The pellet is shown embedded in the fabric and it is seen that the layer which has been in direct contact with the missile is bent almost double around it. Microscopic examination of the actual cross-section reveals that coloured fibres exist all round the pellet, which while causing transverse fabric extension has pushed these fibres in front of it. At the point of contact with the projectile the white portion of the fabric is seen to be highly compressed, and a comparison of fabric thickness around the cone of deformation shows that there has been a concentration of fabric extension in the highly localised area of collision.

Fabric recovery after the defeat of a projectile is clearly seen in this two layer sample. During impact the second layer was highly compacted locally (the outline of the pellet nose is clearly seen) in the effort to prevent missile passage; subsequently when all the pellet energy had been absorbed some relaxation of the inner layer occurred. Fig 20(c) shows the effect of impact on a three layer sample. The same features are apparent - high fabric compaction in the local area of impact (again coloured fibres surround the pellet) and some recovery after the pellet is successfully halted.

6. Conclusions.

Within this chapter it has been shown that the most likely method of energy absorption during needled fabric transverse impact is fibre movement within the structure. This involves a large area of fabric in deformation and high extensions in the area immediately surrounding the impact point. It seems that projectiles do not actually enter the individual layers of fabric but cause their compression at the point of collision. Extension then occurs by the pushing forward of fabric in front of the projectile.

(a)

(b)

(c)

Figure 19

FABRIC SECTIONS SHOWING TRANSVERSE DEFORMATION

CHAPTER IV

ENERGY ABSORPTION BY NEEDLED FABRIC

1. General Concepts

In considering experimental results, it is necessary to bear in mind that there is a discontinuity in the relations between tests which stop the particle and those which allow the particle to penetrate. The force-displacement relations in the two solutions are:

(a) just stopping (b) just penetrating

If the particle is stopped, the area under the curve must equal the impact energy; but if it penetrates there is only a small reduction in energy. It is impossible for a projectile to emerge at slow speed.

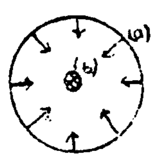
Only the initial region OA of tests which stop the projectile is of any real interest in relation to the effectiveness of protection.

Understanding of the situation is helped when it is realised that there are two distinct features involved in determining whether a projectile will penetrate:

(a) the magnitude of the maximum force developed

(b) whether the maximum force exceeds the force needed to rupture the fabric.

These two features are not simply related. The magnitude of force developed depends primarily on the deformation dynamics at the edges of the deformation region[(a) in diagram]while the penetration force depends on the properties at the region in contact with the projectile; (b) in diagram.



The force development will be related to the stress-strain behaviour of the material (in the simplest case the modulus) and to the material mass; and its prediction will require a proper solution of the wave dynamics. The nature of the stress-strain relations concerned need to be assessed properly in terms of:

1) the geometry of deformation

2) the rate of deformation,

though one might take the ordinary results from a tensile test as a guide.

The penetration force will depend on the area of the particle and the tenacity of the fabric. Once again the geometry and rate effects need to be properly assessed, but either the ordinary strength or a slow speed penetration test might be taken as a guide.

2. Development of Ipson theory.

The theory developed by Ipson and Wittrock (4) can be extended to take account of the above view point. However, it must be remembered that Ipson's theory is based on some rather drastic assumptions including linearity of stress-strain relations, a constancy of parameters, a simplified solution of the wave equation based on the one-dimensional solution and a simplified means of taking account of the radial wave. The spirit of these assumptions is continued and some additional assumptions made in what follows.

Ipson's theory gives the following expression for the projectile velocity during impact.

$$V_p = V_o e^{\frac{-1.86\pi \rho T \sqrt{R}}{Mp} (wt)^{3/2}}$$

V_o = initial projectile velocity

V_p = projectile velocity at time t

ρ = mass density ; T = fabric thickness

R = projectile radius ; Mp = projectile mass

w = transverse wave velocity

If w is assumed constant

$$V_p = V_o e^{-Bt^{3/2}}$$

where

$$B = \frac{1.86\pi \rho T \sqrt{R}}{Mp} w^{3/2}$$

Differentiating:

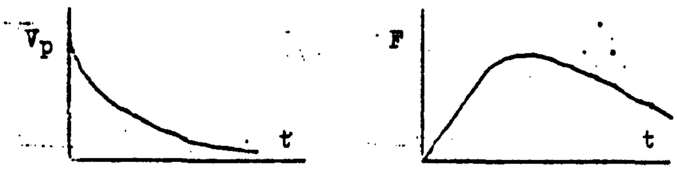
$$\frac{dVp}{dt} = V_o \left(e^{-Bt^{3/2}}\right) \left(-3/2 \; Bt^{\frac{1}{2}}\right)$$

$$= -3/2 \; BV_o t^{\frac{1}{2}} e^{-Bt^{3/2}}$$

The retarding force F is given by:

$$F = -Mp\,\frac{dVp}{dt} = \frac{3}{2}\cdot BM_o t^{\frac{1}{2}} e^{-Bt^{3/2}}$$

where M_o = initial momentum of projectile (Mp.Vo)



Put $F = At^{\frac{1}{2}}\,e^{-Bt^{3/2}}$: where $A = {}^{3}/_{2}\ BMo$

$$\frac{dF}{dt} = A\left[{}^{1}/_{2}\,t^{-\frac{1}{2}}e^{-Bt^{3/2}} + t^{\frac{1}{2}}e^{-Bt^{3/2}}(-{}^{3}/_{2}\,Bt^{\frac{1}{2}})\right]$$

$$= \frac{A}{2}\,e^{-Bt^{3/2}}\left[t^{-\frac{1}{2}} - 3Bt\right]$$

At maximum force $\frac{dF}{dt} = 0$. One obvious solution is:

$$e^{-Bt^{3/2}} = 0 \text{ at } t = \infty$$

But the relevant solution is given by:

$$t_m^{-\frac{1}{2}} - 3Bt_m = 0$$

$$t_m^{-3/2} = 3B$$

$$\therefore\ t_m = (3B)^{-2/3}$$

$$F_{max} = {}^{3}/_{2}\ BM_o\,(3B)^{-1/3}\,e^{-1/3}$$

$$\therefore\ F_{max} = \frac{3^{2/3}}{2}\,B^{2/3}\,M_o\,e^{-1/3}$$

Now, $B = 1.86\pi R^{\frac{1}{2}}\,w^{3/2}\,\left(\frac{Mf}{Mp}\right)$

where M_f = fabric mass/unit area = ρ T

$$\therefore\ t_m = (3B)^{-2/3} = (3 \times 1.86\pi)^{-2/3}\,w^{-1}\left(\frac{Mp}{Mf}\right)^{2/3} R^{-1/3}$$

and

$$F_{max} = \frac{3^{2/3}}{2}\,(1.86\pi)^{2/3}\,R^{1/3}\,w\,\left(\frac{Mf}{Mp}\right)^{2/3} Mo\,e^{-1/3}$$

$$Fmax = \frac{(3 \times 1.86\pi)^{2/3}}{2e^{1/3}} \left(\frac{Mf}{M_p}\right)^{2/3} R^{1/3} \; w \; Mo$$

$$\therefore \; Fmax = \left[\frac{(3 \times 1.86\pi)^{2/3}}{2e^{1/3}} \right] (Mo \; R^{1/3}) \left(\frac{Mf}{Mp}\right)^{2/3} w$$

$$= (\text{Numerical constant}). \; \frac{Mp \; Vo \; R^{1/3} \; M_f^{2/3} \; w}{Mp^{2/3}}$$

$$= K \quad Mp^{1/3} \quad R^{1/3} \quad Vo \quad Mf^{2/3} \quad w$$

$$= K \quad (RM_p)^{1/3} \quad Vo \quad Mf^{2/3} \quad w$$

Numerical constant	Function of projectile	Fabric Mass/unit area	Wave velocity

i.e. $\underline{Fmax = K. f \text{ (projectile)}. \; M_f^{2/3} \; w}$

Fabric failure will occur if $Fmax > F_b$

where F_b = force required for penetration.

For good protection from a useful (i.e. light weight) fabric we need, high F_b, low M_f, low w.

Momentum which produces penetration force F_b is given by

$$(Mo)max = \left[\frac{2e^{1/3}}{(3 \times 1.86\pi)^{2/3}} \right] (R^{-1/3}) \left(\frac{Mp}{M_f}\right)^{2/3} w^{-1} \; F_b$$

As approximations we can put

(1) $$w = \sqrt{\frac{E}{9.81 \times 10^7}}$$

where E is fabric specific modulus (gf/tex)

w is longitudinal sonic velocity

[from equation $E(\text{dynes/cm}^2) = w^2 \text{ (cm/sec) } \rho \text{ (gm/cm}^3)$]

(2) $F_b = 2\pi \alpha R M_f f_B$

f_B is a measure of fabric tenacity

αR is effective fabric radius for rupture

$$\therefore (Mo)_{max} = \left\{\left(\frac{2 e^{1/3}}{3 \times 1.86\pi}\right)^{2/3}\right\} (R^{-1/3}) \left(\frac{Mp}{Mf}\right)^{2/3} 2\pi\alpha FM_f f_B\left[\frac{9.81\times10^7}{E}\right]^{\frac{1}{2}}$$

$$= \left\{\frac{4\pi^{1/3} e^{1/3} (9.81\times10^7)^{\frac{1}{2}}}{(3\times1.86)^{2/3}}\right\} \alpha R^{2/3} \left(\frac{M_p}{M_f}\right)^{2/3} M_f f_B E^{-\frac{1}{2}}$$

$$= \left(\begin{matrix}\text{Numerical}\\ \text{constant}\end{matrix}\right) \alpha M_f^{1/3} (M_p R)^{2/3} \frac{f_B}{\sqrt{E}}$$

Now $(Vo)_{max} = \dfrac{(Mo)_{max}}{Mp}$

where $(Vo)_{max}$ is maximum projectile velocity which the fabric can sustain. This is close to V_{50} for a variable specimen.

$$(Vo)_{max} = (N.C) \alpha \frac{R^{2/3}}{M_p^{1/3}} M_f^{1/3} \frac{f_B}{\sqrt{E}}$$

$$\underline{(Vo)_{max} = K R^{2/3} \left(\frac{Mf}{Mp}\right)^{1/3} \frac{f_B}{\sqrt{E}}}$$

where K is a constant involving the numerical constant and α.

If f_B is assumed to be fabric tenacity during a uniaxial tensile test, and E fabric specific modulus during such a test, then

$$E = \frac{f_B}{e_B} \quad \text{where } e_B = \text{fabric breaking strain}$$

$$\therefore \sqrt{E} = \sqrt{f_B/e_B}$$

$$\therefore \frac{f_B}{\sqrt{E}} = \sqrt{f_B e_B}$$

If W = fabric work of rupture, assuming linearity of the stress-strain curve.

$$W = \tfrac{1}{2} f_B \, e_B$$

$$\therefore \quad f_B \, e_B = 2W$$

$$\therefore \quad \frac{f_B}{\sqrt{E}} = \sqrt{2W}$$

Thus:

$$(V_o)_{max} = K^1 \, R^{2/3} \left(\frac{M_f}{M_p}\right)^{1/3} \sqrt{W}$$

where $K^1 = K\sqrt{2}$

In order to test the validity of this equation, needled felt of known V_{50} values would be subjected to uniaxial tensile tests to determine work of rupture. Different fabric weights should be employed, as well as projectiles of varying radius and weight.

Attempts should also be made to develop more realistic treatments of some parts of this analysis.

3. Fabric characteristics

Energy absorption by needled fabric during transverse impact will take place initially by fibre straightening and alignment within the structure. When this process is complete and if the projectile is still not halted, fibre slippage will occur; if this is excessive fabric breakdown takes place. Both these mechanisms will be accompanied by fabric extension which is easily achieved during initial loading but subsequently becomes more limited as fibres lock together. Thus the essence of energy absorption by needled felt involves relatively large fabric extensions. The optimum needled fabric for ballistic purposes will be attained by increasing the resistance of the fabric by means of a combination of the variables discussed within Chapter 2 without destroying the slippage mechanism. Total restriction on fibre movement after the straightening and alignment stage will allow a projectile to totally penetrate the fabric by means of fibre breakage. The energy absorption process inherently involves fabric extension but this must be reduced to a minimum for practical applications of this material without impairing efficiency. This can be achieved to some extent by variation of web and machine parameters employed during manufacture, but unless fabric weight is increased to unacceptable limits (i.e. no advantage over woven fabric), where efficiency is somewhat reduced by lack of freedom of response to impact, it seems that transverse extension will be a drawback to usage of this material. It is interesting to note that in previous work (4) the fabric providing the best resistance exhibited the greatest extension.

Extension can be restricted by increasing the frictional forces between fibres, but if too much resistance to movement is generated in this fashion, fabric breakdown will again occur through fibre breakage.

Another method of gripping fibres more tightly in the structure is to increase needling density. If a felt is produced at very high needling density fibre movement will be restricted and fabric extension reduced. Under those conditions little energy will be absorbed during impact as the tightly gripped fibres will themselves be broken without the energy absorbing mechanisms becoming fully operative. In contrast if a web is needled too little there will be less resistance to straightening, and fibres will immediately slip. Such fabric will extend to a greater extent but in so doing does not realise the optimum energy absorption capabilities of the needled structure, as little or no resistance is applied by means of vertical tufts to initial straightening and alignment.

Optimum needling density will depend on web weight and must also be considered together with depth of needle penetration. It has already been shown that the optimum values of needling density and needle penetration for one web weight, may be of little use in strengthening a web of different weight. The highest possible penetration should be employed without destroying all the contact between vertical and horizontal structure, as this increases the size of individual tufts within the fabric and thus the energy absorbed during the fibre straightening process. The optimum value of needling density will have the same effect, and also increase the force required to cause fibre movement during subsequent slippage.

A large area of fabric is affected by impact because the individual units of the material i.e. the fibres, are not continuous and in themselves provide no resistance (although the choice of fibre type affects the transfer of fibre strength into needled fabric strength); this originates from their combination in the needled felt structure and the realisation of strength in this structure by extension, during which energy is absorbed from a projectile.

This discussion relates to the factors desirable in a single layer of felt. For ballistic purposes felt will be best used as a combination of several unattached layers. This will provide far greater flexibility of the structure and a better response to impact.

The variables employed during production will govern the response of individual fabric layers to the impact process. Theoretical work earlier in this chapter has shown the importance of the transverse wave velocity set up on impact. The maximum force set up during collision was shown to be directly proportional to fabric mass per unit area (to the power of 2/3) and wave velocity. The value of this wave velocity must be sufficiently high so that energy is dissipated widely within the fabric otherwise rupture will occur easily, but not too high or the strain imposed at any point will be too great for the material to withstand.

The experimental results of Ipson & Wittrock (4) showed that a nylon fabric gave the lowest value of F_{max} within the range of fabrics they tested but the greatest value of extension.

Similarly it was shown that the time required to reach this maximum force is inversely proportional to the same factors. Thus by reducing the value of wave velocity maximum force is decreased but the time over which it is sustained by the fabric increased; with a consequent possible increase in fabric transverse extension. The experimental results of Ipson and Wittrock (4) showed that the nylon fabric they tested showed the lowest value of F_{max} within the range of fabrics they tested but the greatest value of extension.

It seems that although maximum force can be reduced thus making fabric breakdown less likely, this must be accompanied by greater transverse extensions as the projectile velocity is nullified over a longer period of time.

4. Future work.

The work reported here indicates that the following aspects of the problem merit further study.

(a) A proper derivation of the dynamics. For the reasons put forward by Ipson an analytical solution is very difficult to obtain, and probably of little use in that it would be restricted to a particular stress-strain relationship. A more promising route would be a computer simulation, enabling the behaviour of materials with various properties to be predicted.

(b) In the absence of a full theory the approximate theory should be tested for validity by means of a greater experimental programme. It should be possible to test the influence of parameters

$$R, \quad M_p, \quad \frac{M_f}{M_p} \quad \text{and} \quad f_B/\sqrt{E}$$

(c) The question of what are the appropriate 'strengths' and 'moduli' to take account of should be studied experimentally and theoretically. This is essentially a study of what are the appropriate material properties to substitute in the dynamic analysis, or, in the absence of a full analysis in the approximate theory developed above.

(d) The relation of the relevant material properties to the needled fabric structure (and ultimately the production process) and fibre properties should be further studied.

(e) The behaviour of composite systems should be examined, namely multiple layers of fabric and fabric backed by the body. There are indications in the present work that a simple summation is not an adequate representation of the behaviour. The dynamic response and the force required to penetrate the fabric are likely to be different in the whole system.

(f) Recognition of the nature of maximum and penetration forces and of the areas to which they are related might lead to the development of improved materials with a more complex geometry which leads to a high resistance to penetration over a small area while giving a low modulus for large scale deformation.

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